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An MILP modeling approach to systemic energy technology valuation in the 21st century energy system

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Abstract

New cannot be measured with old. The transformation of the electricity system from a network of fossil-based dispatchable power plants to one with large amounts of intermittent renewable power generation, flexible loads and markets, requires a concurrent development of new evaluation tools and metrics. The focus of this research is to investigate the value of power technologies in order to support decision making on optimal power system design and operation. Technology valuation metrics need to consider the complexity and interdependency of environmental and security objectives, rather than focusing on individual cost-competitiveness of technologies outside of the power system. We present the System Value as a new technology valuation metric, based on a mixed-integer linear program (MILP) formulation of a national-scale electricity system. The Electricity System Optimization model is able to capture detailed technical operation of the individual power plants as well as environmental and security requirements on the system level. We present a case study on the System Value of onshore wind power plants in comparison with Carbon Capture and Storage (CCS) equipped gas-fired power plants in a 2035 UK electricity system. Under the given emission constraints, the deployment of both technologies reduce total system cost of electricity generation. In the case of CCS-equipped power plants the reductions in total system cost are 2 to 5 times higher than for the deployment of onshore wind capacity.

Keywords: electricity systems modeling, technology value, Carbon Capture and Storage, onshore wind

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1. Introduction

The urgent need to mitigate greenhouse gas emissions has made a far-reaching and fast transition in the energy sector unavoidable. The resulting trilemma of carbon avoidance, system security, and the maintenance of low energy cost summarizes the challenge of the 21st century energy system. We are observing changes on the power supply side, as dispatchable fossil-based generation is decreasing and power generation from intermittent renewable energy sources (iRES) increases. At the same time, the power demand is changing in scale and shape, driven by progressing electrification of the transport and heat sector. Both effects amplify the requirements for power system services that ensure the security and operability of the network [1, 2]. These so called ancillary services are receiving increasing attention in energy policies such that their provision is beginning to generate new markets for power plant operators and energy-intensive industries. The lines between power generators and consumers is beginning to blur.

New requirements are being imposed on power generation, storage, transmission, and information technologies. On the generation side, characteristics such as the carbon intensity, flexibility, and availability are gaining further importance. Technologies have to coordinate activities and function in a tightly integrated network. As the complexity of interactions increases, it becomes more difficult to understand the advantages of specific electricity generation technologies. Existing approaches fail to address:

- The variety of power system services, e.g., reserve, frequency and voltage control, flexibility [3]
- The time and space of service provision, i.e., the heterogeneity of electricity generation, the difference between dispatchable and intermittent power generation [4, 5]
- Implicit features, e.g., back-up or transmission reinforcement requirements, reduced full-load hours, associated carbon emissions [6]
- Market dynamics, e.g., varying electricity prices, investment risk, and uncertainties [7]

The Levelized Cost of Electricity (LCOE) is a widely used metric to compare and evaluate the profitability of power generation technologies. It sets the costs incurred throughout the lifetime of a power plant in relation to the generated electricity output, creating a single value measured in £/MWh. However, all of the above mentioned shortcomings apply to the LCOE metric [7]. However, in the context of the above-described complex energy systems, metrics which consider technologies in isolation are inadequate for their task of technology evaluation. In addition to system transitions in power generation, demand, and the new low-carbon obligations of the 21st century, the metrics used to evaluate the applicability and profitability of a power technology has to be redesigned.

We propose a new technology valuation metric – the System Value – considering the systemic aspects of technology integration based on mathematical modeling of a national-scale electricity system. The following section 2 introduces the System Value concept in detail. Section 3 presents a case study on the System Value of onshore wind and abated gas fired power plants. Section 4 concludes.

2. The System Value

2.1. Conceptual framework and algorithm

The System Value (SV) of a technology is defined as the marginal change in total annual electricity system cost (capital, energy, ancillary services) caused by the technology's capacity deployment relative to the amount of installed capacity. A technology has a *value* to the system if its deployment reduces the total system cost. Consequently, the SV is a direct function of the system composition within which the technology is operating and the level of capacity deployment, resulting in a £/kW value.

Taking a whole systems perspective, the SV metric explicitly accounts for the power plant interactions, effects such as back-up and frequency control requirements, increased thermal power plant shut-down and start-up, cycling-induced CO_2 emissions. These effects are often referred to as "integration cost" and "associated carbon" and have yet found limited attention in economic technology assessment tools [5, 6, 8]. The SV algorithm, however, determines the total system cost by explicitly accounting for these contributions to whole system cost via a mathematical optimization model of a national-scale electricity system. From the perspective of the centralized power systems planner we determine the optimal generation capacity mix and the hourly power plant schedule for one year of operation, while considering system-wide security and operability constraints, as well as overall carbon emission targets.

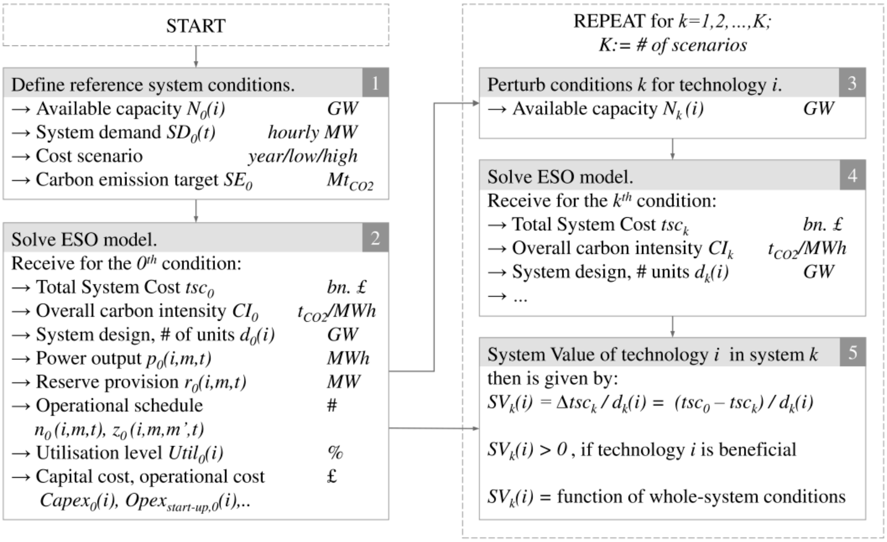

Fig. 1. Algorithm to derive the System Value (SV) of a power generation technology with the Electricity Systems Optimization (ESO) model and critical parameters, variables, and outputs in each step 1 to 5.

Figure 1 outlines the procedure to derive the System Value of a power generation or energy storage technology. In step 1, the reference system conditions are defined by specifying the amount of available capacity for each type of power technology, the hourly electricity demand, ancillary service requirements, carbon constraints, costs, and technology characteristics. We note that the level of available capacity sets the upper bound for the deployment of each technology within the ESO model and is always greater or equal to the amount of installed capacity of each technology. Here the upper bound for the observed technology *i* is set to zero, such that the reference case represents the system characteristics without technology *i*.

Step 2 represents the centerpiece of the SV algorithm, the solution of the ESO model yields the optimal system design (capacity per technology) and hourly schedule, here without availability of technology *i*. The ensuing steps 3 to 5 are repeated for *K* scenarios, representing different levels of capacity availability of technology *i*. In step 3, the desired capacity availability of technology *i* is adjusted to a value greater than zero, initially the size of one typical capacity unit (100 MW -1 GW). The ESO model is solved in step 4. If the deployment of technology *i* is valuable to the system it is then part of the optimal resulting capacity mix. In step 5, the calculated Total System Costs (TSC) are compared with the reference system and the system containing capacity of technology *i*. The SV of technology *i* is then derived as a function of the incumbent system and the level of technology deployment by relating the TSC reduction to the amount of installed capacity of technology *i*.

As opposed to the LCOE metric, a technology valuation via the SV metric obtains not a single answer but a value function. It can explicitly indentify the value development as a technology penetrates into the market. The possibility to differentiate between the value of the first capacity unit (first-of-a-kind) and the nth capacity unit (nth-of-a-kind) is, to the best of our knowledge, a unique feature of the SV metric.

2.2. Electricity Systems Optimization Model – ESO

The Electricity Systems Optimization (ESO) model is formulated as a mixed-integer linear program (MILP). It is highly modular allowing for the combination of a large range of power generation and storage technologies and adjustment to different national electricity systems.

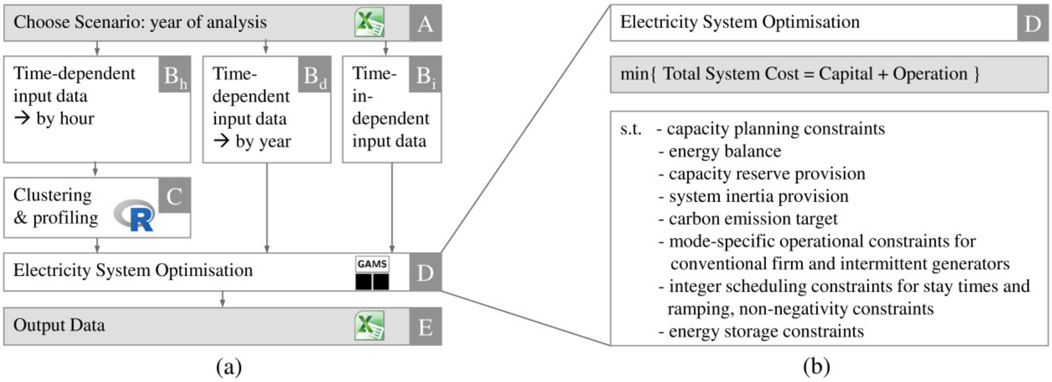

Fig. 2. (a) Structure of Electricity Systems Optimization (ESO) model integration and software application; (b) Outline of ESO model formulation as MILP.

Figure 2 (a) summarizes the ESO running procedure and complements the conceptual framework in figure 1 with the applied software tools. Figure 2 (b) outlines the mathematical structure of the MILP formulation. We aim to minimize total annual electricity system cost, subject to a set of linear continuous and integer constraints. The system-wide constraints on energy, reserve, system inertia, and carbon emissions address the two crucial aspects of the energy trilemma: system security and carbon avoidance. The objective function on cost minimization considers the third aspect. Detailed operational constraints describe the switching between different operational modes (starting-up, on, off) with their respective minimum stay times in each mode for conventional thermal power generators. IRES technologies as well as electricity imported from electric interconnectors are modeled in a binary on/off fashion with a respective continuous range of power output limitations. Another set of constraints defines the operational bounds of energy storage technologies, considering charging/discharging/inventory limits, and the state of charge balance. We omit network transmission constraints and assume that generation and load occur at a single node. The underlying formulation, excluding the set of storage constraints, is described in detail in Heuberger et al. [9]. The model is formulated in GAMS 24.6.1 and solved with CPLEX 12.3.

The ESO model is an investment and planning tool with a focus on technical and operational detail. The hourly time discretisation is able to sufficiently capture the effects of intermittent power generation on the nation-level electricity system level. In addition to the capacities which establish system adequacy, the ESO model is able to estimate sufficient amounts of capacity providing reserve and operability services while simultaneously determining the optimal operational schedule of all power plants installed. We can review proposed transition pathways for the electricity sector and compare those to the societal optimal solution which we receive as an output of the ESO model. It can support policy makers in determining appropriate support strategies for power technologies as it highlights a technologies specific value to the electricity system.

3. Case study on the System Value of CCS and wind capacity

3.1. Technology and system data preparation

We apply the ESO model and SV metric to a potential 2035 UK electricity system, which is characterized by a strong carbon emission target of 16 Mt_{CO2}/year, tantamount to an 80 % reduction compared to a 1990 baseline [10]. Upper bounds for the available new-build generation capacity refer to DECC's† reference scenario [10]. Underlying fuel price estimates and system security constraints on capacity reserve and system inertia can be found in [11] and [12]. System reserve is modeled as a fixed capacity margin in addition to a factor dynamically matching the amount of intermittent capacity which is online in each hour of operation. Table 1 summarizes salient input data for the two technologies analyzed in detail in this study, and the 2035 conditions of a UK-like electricity system.

Table 1. Input data for a Combined Cycle Gas Turbine (CCGT) equipped with post-combustion CCS [13], onshore wind power plan [14], and the 2035 UK electricity system [10]. CAPEX are annualized at 7.5 % discount rate and an economic lifetime of 25 years. The capacity margin refers to the system-wide de-rated capacity reserve. Hourly electricity demand is scaled up by 22 % [10, 15] from 2014 values [16].

Symbol	CAPEX	$CAPEX_{ann.}$	Full-load OPEX	Carbon Intensity	Symbol	Electricity demand	Peak demand	Reserve margin	System Inertia	Emission target
Unit	£/kW	£/kW-year	£/MWh	t_{CO2}/MWh	Unit	TWh/year	GW	%-GW	GW.s	Mt_{CO2}
CCGT-CCS	1187.3	119.11	43.9	0.041	System	354	62	4	100	16
Wind	1105	104.38	0	0						

In order to efficiently solve the ESO model and reduce the solution time, we apply a data clustering and profiling method to all hourly input data sets. The clustering technique is based on the *k*-means clustering approach which organizes the data into *k* clusters by minimizing the Euclidean distance for each data point from the mean value of the cluster *k*. The solutions of the ESO model are rescaled to annual values with the respective weight of the cluster *k*. We chose a cluster length of 24 hours and find that a number of 21 clusters (1 being the day including peak demand, 20 representing the remaining days) yields a good trade-off between solution time and accuracy. Results obtained from the clustered data set lead to an average underestimation of 1 % for system-wide and 4 % for technology-specific variables compared to the full hourly data for one year of operation. For each data cluster, a representative specific hourly profile, preserving the mean energy level of the data cluster, is chosen for the onshore wind, offshore wind, solar availability, and electricity demand profiles. The clustering and profiling technique achieves a model size reduction from approximately 4,000,000 variables in the model using the full data set to 200,000 in the clustered version.

3.2. The system impact and value of CCS capacity

In the SV concept, a power technology is valuable if it is chosen as part of the optimal capacity mix. The SV metric assigns value to a power technology if the Total System Cost (TSC), including capital cost and operational expenses of all generation and storage technologies, are less with the integration of the observed technology than without.

Under the given system conditions, we apply the SV approach to a Combined Cycle Gas Turbine (CCGT) power plant equipped with a post-combustion Carbon Capture and Storage (CCS) process operating at 90 % CO_2 capture rate. We increase the upper limit of available capacity for the observed technology and determine the "economic limit of deployment" as result of the ESO design. Up to this level, a capacity addition of the observed technology reduces the TSC further, classifying it as valuable.

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† Now combined into the Department for Business, Energy and Industrial Strategy.

Figure 3 visualizes the optimal capacity mix and the TSC depending on the system requirements stated in table 1 and the available CCGT-CCS capacity. The initial capacity stack at zero CCGT-CCS availability shows the optimal technology mix under 2035 system conditions and the corresponding TSC. We find that the integration of CCGT-CCS capacity is valuable as the TSC decrease upon CCGT-CCS deployment. Significant amounts of CCGT-CCS capacity are part of the cost-optimal mix to achieve carbon emission targets while ensuring system reliability and operability. The integration of CCGT-CCS capacity can displace offshore wind and interconnection capacity, reducing total capacity requirements and the UK's energy dependency. At 52.5 GW CCGT-CCS reaches its economic deployment limit. We note that this theoretical limit is high; the integration of energy storage and demand side technologies could have the potential to complement the deployment of low-carbon iRES technology. Such analysis is out of scope for this study. However, in the absence of sufficient balancing capacity firm low-carbon capacity such as CCGT-CCS is highly valuable and has the potential to achieve a TSC reduction of 28 % at 30 GW and 30 % at the economic deployment limit.

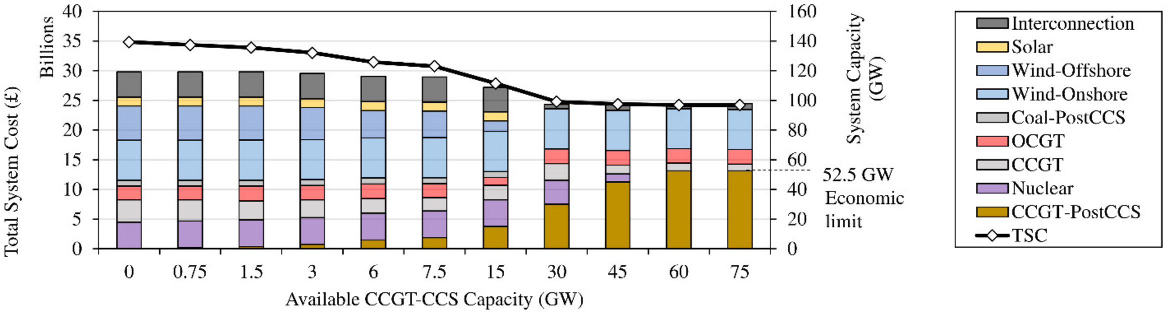

Fig. 3. Total System Cost and Capacity as a function of available CCGT-CCS capacity.

3.3. The system impact and value of onshore wind capacity

We perform the equivalent SV analysis for onshore wind capacity under 2035 system conditions. As a function of onshore wind capacity availability figure 4 visualizes the optimal capacity mix and TSC. We find that the integration of onshore wind capacity is valuable to the electricity system and reduces TSC. Due to a low availability and operational expenses, larger amounts of capacity are valuable and the economic deployment level is reached at 84.82 GW. However, as opposed to the integration of CCGT-CCS, the deployment of onshore wind capacity increases the total amount of necessary capacity by 50 % from 98 to 148 GW at the maximum deployment level. Offshore wind and solar capacity is displaced as power generation from onshore wind is more cost-effective per MWh generated. We note, that spatial resource constraints are not taken into consideration and the presented economic limit is a theoretical deployment ceiling.

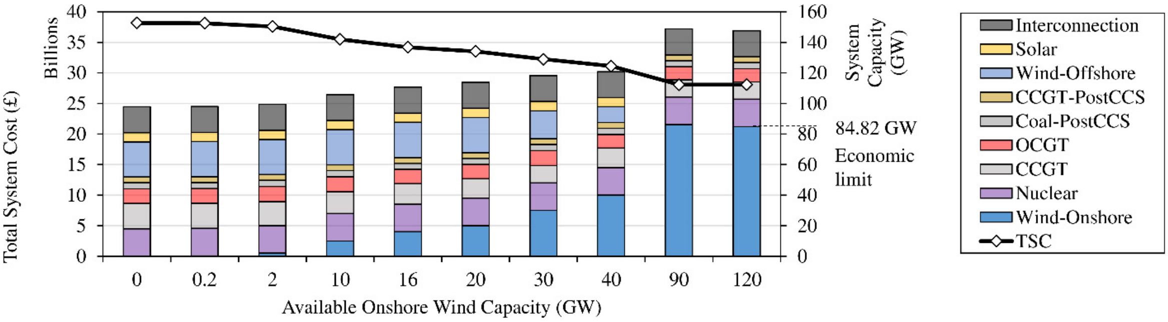

Fig. 4 Total System Cost and Capacity as a function of available onshore wind capacity.

Remaining unabated fossil-based capacity from CCGT and OCGT power plants can be reduced by 23 % at the maximum onshore wind deployment level. Low-carbon capacity such as nuclear, CCS-equipped coal and CCGT cannot be displaced by an increase in onshore wind capacity as it remains necessary to hold large amounts of firm capacity in the system. At the same time, their annual average utilization factor decreases (i.e., 74 to 70 % for nuclear, 60 to 57 % for CCS-equipped power plants), as thermal power generation is increasingly crowded out and held as back-up capacity. A significant amount of interconnection capacity remains part of the cost-optimal capacity mix. The theoretically achievable TSC reduction upon onshore wind capacity deployment reaches 16 % at 30 GW of deployed capacity and 26 % at the economic limit.

4. Conclusion

Technology-isolated cost-based evaluation metrics are rapidly becoming inappropriate for application to the complex electricity system of the 21st century. The interaction between power generation and demand, the transmission and distribution of electricity, in addition to environmental and security requirements must be accounted for when assessing the suitability of a power technology in a given power system. We have developed a technology valuation metric, the System Value (SV), which assigns value to a power technology if its deployment reduces the total cost (capital and energy) of the electricity system. The SV of a power technology is not a single value but a function of the incumbent system design and constraints. It is based on the national-scale Electricity System Optimization (ESO) model which takes hourly system dynamics (e.g., intermittency of power generation, ancillary services) and long-term system conditions (e.g., carbon emission target, security requirements) explicitly into account.

For a future UK-like electricity system in 2035, we have demonstrated the SV concept and evaluated CCS-equipped CCGT and onshore wind capacity. The deployment of both low-carbon technologies could significantly reduce the total system cost of electricity generation, with CCGT-CCS showing an even greater value of e.g., £500/kW compared to £270/kW reduction with onshore wind, both at 10 GW of deployment. However, we have shown that the value of a technology depends on the level of capacity penetration into the system as well as on the prevalent capacity mix and system constraints. It is therefore imperative to assess the value of a power technology in a systemic context rather than in isolation.

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